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James C. Yu
Langley Research Center
Hampton, Virginia

A. Louis Abrahamson
COMTEK
Grafton, Virginia

National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

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The NASA study committee appointed to carry out the feasibility study on acoustic treatment of the NASA Langley 4- by 7-Meter Tunnel was comprised of the following:

John P. Raney (Chairman)	Structures Directorate
Robert W. Feldhousen	Systems Engineering and Operations Directorate
Robert A. Golub	Structures Directorate
Earl C. Hastings, Jr.	Aeronautics Directorate
Danny R. Hoad	Army Aerostructures Directorate
Robert E. Satterthwaite	Systems Engineering and Operations Directorate
James C. Yu	Structures Directorate

The Acoustics Division of the Structures Directorate assumed major responsibility for the study. In addition to the institutional resources available to the committee, the services of Bolt Beranek and Newman (BBN) Inc., COMTEK, and DSMA Engineering Corporation were utilized to conduct specific diagnostic and engineering tasks identified by the committee.

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Emanuel Boxer	Aeronautics Directorate
Zachary T. Applin	Aeronautics Directorate
Sheridan R. Barringer	Systems Engineering and Operations Directorate

SUMMARY

This report describes a feasibility study for upgrading the NASA Langley 4- by 7-Meter Tunnel so that it may be used for aeroacoustic research related to helicopters. Although rotor noise research in wind tunnels is not a new concept, the requirements for noise research leading to the design of the next generation of helicopters impose a set of acoustic test criteria that no existing wind tunnel in the United States can presently meet.

Included in this feasibility study are the following considerations: (1) an evaluation of general wind-tunnel requirements for helicopter aeroacoustic research, including the establishment of desired tunnel background noise levels for such research, (2) an assessment of the present acoustic environment for testing model rotors in the Langley 4- by 7-Meter Tunnel, (3) a diagnostic investigation of tunnel background noise sources and paths, (4) the establishment of acoustic treatment options for tunnel background noise reduction and a description of a trade-off study between these options, (5) an engineering feasibility assessment of the selected option, and (6) a final integrated analysis of the various study components and recommendations for an approach to meet the tunnel background noise reduction goal.

It is concluded that the Langley 4- by 7-Meter Tunnel is a fundamentally suitable facility for helicopter aeroacoustic research. It is also concluded that acoustic treatment of this facility for meeting the required tunnel background noise goal can be accomplished technically at reasonable risk and cost.

1 INTRODUCTION

The use of helicopters in the civil air transportation market is projected to increase. If present acoustic design technology is used for this future commercial market, then unacceptable community noise levels may be anticipated. Research in quiet helicopter technology is urgently needed now so that the new generation of rotorcraft will meet acceptable community noise standards. NASA's commitment to a long-term joint research and development program with major U.S. helicopter manufacturers - referred to as the "NASA/American Helicopter Society (AHS) National Rotorcraft Noise Reduction Program" - was made in response to this anticipated helicopter noise problem (ref. 1).

The ultimate objective of the NASA/AHS program is to provide technology for predicting and reducing noise radiation from helicopters at the design state. A critical requirement for this needed research is a high-quality low-speed wind tunnel suitable for aeroacoustic research of powered scale model helicopters.

A wind tunnel is essential for rotorcraft noise research because of aeroacoustic effects that exist only in forward flight and, therefore, cannot be investigated by the study of hovering rotors. The complex nature of the noise field generated by a helicopter rotor system is strongly dependent on the highly distorted three-dimensional flow created by the rotor blades. This flow can involve nonlinearities and transient effects that are not present in the flow over hovering rotors.

Rotor noise research in wind tunnels is not a new concept. Acoustic measurements have been made for many years on scale model rotor systems in wind tunnels. (For example, see refs. 2 to 7.) Although the wind-tunnel/model-rotor combination has been shown to be a highly effective experimental configuration for studying certain dominant mechanisms of helicopter noise generation, past research has been limited by the unavailability of a wind tunnel in the U.S. that is suitable for a wide range of system noise measurements for the model helicopter.

Accentuating the limitation of existing wind tunnels is the fact that manufacturers now anticipate facing community noise certification requirements that specify the use of a perceived noise level as a noise metric. This category of noise metrics emphasizes the midrange frequencies to which the human ear is most sensitive. The aeroacoustic broadband mechanisms that appear to dominate noise generation in this frequency region are not fully understood and are difficult (if not impossible) to measure in existing facilities because of the relatively high level of facility background noise.

Before discussing desirable characteristics of a wind tunnel suitable for acoustic testing, it is appropriate to define two terms - "test section" and "test chamber" - that will be used in this report. The test section in all wind tunnels is that portion of the wind-tunnel circuit within which the model under test is located. Usually, the test section is bounded by the tunnel walls just as in the rest of the tunnel circuit. (See, for example, ref. 8.) Some wind tunnels are also designed to operate in an open test section mode such that the flow exits from a nozzle into one side of the test chamber, is collected at the opposite side of the test chamber, and then is redirected back around the circuit. In this case, the test section consists of the potential core region of the free jet. A schematic drawing in figure 1 of the Langley 4- by 7-Meter Tunnel circuit, which may be operated in both open and closed test section modes, is used to illustrate this concept.

In wind tunnels used only for aerodynamic testing, the terms "test section" and "test chamber" are interchangeable; but for the case of acoustic testing in which noise measurements may be made in any part of the test chamber, including outside the flow itself (that is, outside the test section), the distinction between these two terms becomes important.

Essentially, a wind tunnel suitable for acoustic measurements of helicopter system noise, including the rotor broadband noise sources, should meet the following four general requirements:

1. Flow quality (ref. 9) - For adequate investigation of aeroacoustic source mechanisms, tunnel flow should be highly uniform (within 0.5 percent) and possess a very low turbulence level (a maximum of 0.5 percent). Also, the mean flow unsteadiness should be minimal (less than 0.5 percent).

2. Test section size - Because the mechanisms of rotor noise generation and their associated scaling relations from model to full-size rotors are inadequately understood, there is a minimum desirable scale from which full-scale results may confidently be inferred. This minimum scale has been estimated from consideration of Reynolds number and known noise-generation mechanisms to be of the order of 1/5-scale. This translates to a minimum model rotor diameter of about 2 m. Testing of 1/5-scale rotorcraft models mandates the use of a large wind tunnel with a uniform flow region in the test section at least 4 m wide to allow an adequate flow-boundary clearance for the model.

3. Background noise level - Numerous potential noise sources exist in a wind tunnel and special consideration of each possible source is necessary to minimize unwanted background noise in both the tunnel test section and test chamber. Good acoustic measurement practice dictates that accurate measurements of rotor noise sources can be made only when noise from these sources is at least 6 dB above the background noise at all frequencies of interest. Sophisticated methods for extraction of lower-level noise sources do exist but are time-consuming and require some prior knowledge of the source. They are thus not recommended for routine measurements. Development of a working criterion for tunnel background noise for rotorcraft testing is summarized in section 2.3.

4. Large anechoic test chamber surrounding open test section - As discussed earlier, the term "open test section" refers to a wind tunnel that may be operated in a free-jet mode. In this mode of operation, the airstream through the surrounding test chamber consists of a free jet of sufficient size to include the test model fully in its potential core. For rotorcraft aeroacoustic testing, this mode of operation is highly desirable and arises from several related considerations.

   Since a rotor is a geometrically large acoustic source, measurements in the geometric far field, say at a minimum distance of 2.5 rotor diameters from the hub, require microphone positions at least 5 m from the model center for a 2-m rotor. For a tunnel that can operate only in a closed test section mode, this increases the minimum required lateral test section dimension to 10 m without any allowance for anechoic wall treatment or wall/microphone separation. For a tunnel operable in an open test section mode, a much smaller test section size is required since measurements can be made outside the flow in the test chamber.

   Acoustically absorbent wall treatment is essential for the test chamber of a wind tunnel to approximate an acoustic free field condition. If the surfaces of the test chamber reflect sound, then acoustic measurements will contain not only directly incident sound but also the contributions from multiple reflections. These additional contributions can severely complicate the task of interpreting measured data.

   The performance of acoustic treatment used on wall surfaces exposed to flow is generally inferior to that typically used in anechoic chambers (that is, acoustic wedges), where the acoustic treatment is not required to withstand flow. Thus, it is only in a tunnel with an open test section surrounded by a large anechoic chamber, where the acoustic treatment is not exposed to flow, that the measurement capability can approach that of a free field.

   Another advantage of an acoustically treated open test chamber (which was quantified during the course of this study) is that lower background noise levels exist at out-of-flow acoustic measurement positions. This difference arises from the absence of flow-induced microphone self-noise at out-of-flow positions and the directivity of tunnel circuit noise radiated into the measurement space. (See sections 2 and 4.)

A survey of existing U.S. wind tunnels revealed that no adequate facility that presently meets the requirements for acoustic measurements of all pertinent helicopter noise sources either exists or is being planned. Indeed, even on a worldwide basis, only one facility exists that apparently possesses the necessary features. This facility is the German-Dutch (Duits-Nederlandse) Wind Tunnel (DNW) at Noordoostpolder in the Netherlands. (See refs. 10 and 11.)

Since the construction of a new wind tunnel is not considered feasible, the alternative is to examine an existing promising candidate for modification. This rationale resulted in the consideration of the Langley 4- by 7-Meter Tunnel.

The Langley 4- by 7-Meter Tunnel (previously known as the V/STOL Tunnel, and frequently referred to hereinafter as the "4 × 7-m Tunnel") was specifically designed for aerodynamic testing of V/STOL models and recently went through a major modification for flow quality improvement, thus satisfying the first two aforementioned requirements. Although acoustic testing was not considered in the design, the provision of an open test section and a large test chamber surrounding the open test section offered the possibility of satisfying the additional requirements. Because of these favorable factors, this tunnel and the Ames 40- by 80-Foot Wind Tunnel were suggested by NASA's Aeronautics Advisory Committee (AAC) Rotorcraft Subcommittee for an in-depth treatment feasibility study.[1] Subsequently, an ad hoc study committee for this purpose was formed at the NASA Langley Research Center.

Throughout the study, the activity associated with providing necessary background information, and with justifying conclusions by comparison with similar facilities (especially with the DNW), yielded valuable insights into the behavior and design characteristics of wind tunnels suitable for rotorcraft acoustic testing. Several of the conclusions emerged only after a final review and analysis of the various study components. The purpose of this report is to describe the process by which the study was carried out and to document conclusions that pertain not only to the 4 × 7-m Tunnel but also to acoustic wind tunnels in general.

A summary of the components of the feasibility study follows in sections 2 and 3. Section 4 contains a final review and integrated analysis of the various study components.

2 STUDY COMPONENTS

In this section, the major study components are summarized as follows: (1) microphone placement, (2) assessment of geometrical constraints, (3) determination of goals for tunnel background noise level, (4) quantification of acoustic sources and paths within the tunnel, and (5) establishment of options for background noise reduction in the tunnel test chamber.

Study components (2) and (3) are documented in reference 12, and (4) and (5) are in references 13 to 16. The purpose of this section is to highlight the significant portions of this work.

[1]Report of the AAC ad hoc Rotorcraft Subcommittee meeting at NASA Headquarters July 27-28, 1982.

2.1 Microphone Placement

For rotorcraft acoustic testing in wind tunnels with an open test section such as in the 4 × 7-m Tunnel, proper consideration must be given to the placement of measurement microphones in order to achieve the specific test objectives. Seven major factors need to be evaluated, and these are illustrated in figure 2. As shown in the figure, rotor noise can be classified into two main categories: periodic noise (including impulsive noise) and random noise. This classification is appropriate when sound transmission through the shear layer of the free jet is considered. For any rotor acoustic test, measurement microphones may be placed either inside the test flow (the uniform portion of the free jet) or outside the test flow (in the acoustically treated test chamber), depending largely on the purpose of the test and the specific type of noise source to be measured.

For in-flow microphones, the lower bound of the background noise is usually determined by the pressure fluctuations induced by either the free-stream turbulence or the boundary layer developed over the nose cone of the microphones. These pressure fluctuations are in the form of a pseudosound and are often referred to as the "microphone self-noise." An extensive study on in-flow microphone self-noise was carried out by Noiseux (refs. 17 and 18). (See also the discussion in appendix G of ref. 13.)

For out-of-flow microphones, the noise radiated by the tunnel test flow and tunnel circuit components determines the lower bound of the background noise, and in a quiet wind tunnel this is lower than the in-flow microphone self-noise. The principal disadvantage with out-of-flow measurements, however, is that transmission of source noise through the shear layer of the free jet requires corrections. Sound transmission through a shear layer has been extensively studied. (See, for instance, refs. 19 and 20.) The general conclusions that can be drawn from these studies are as follows:

1. Correction of shear layer transmission effects can be made with confidence for random noise.

2. Correction can also be made to the periodic or impulsive noise if the spectral bandwidth is 1/3 octave or wider, and provided that data for turbulence scattering are obtained for the tunnel shear layer through calibration.

3. If the waveform of the periodic or impulsive noise is of interest, and if the signal contains significant high-frequency components, then transmission of a signal through the shear layer tends to distort the waveform and this distortion cannot be corrected.

By considering collectively the seven factors listed in figure 2, the following may be concluded: (1) for measurements related to a rotor system noise study, in which all sources (periodic, impulsive, and random) need to be considered but where a 1/3-octave-band sound pressure level (SPL) is adequate, out-of-flow microphone measurements represent the best choice; (2) for measurements in which accurate determination of noise waveform is vital (periodic or impulsive noise only), microphones should be placed inside the test flow in order to avoid waveform distortion from turbulence scattering; and (3) for measurements in which both system noise and signal waveform are of interest, measurements should be made with a judicious combination of both in-flow and out-of-flow microphones.

It should be noted that rotorcraft system noise is of concern in community noise problems and that signal waveform is important to the understanding of the source mechanisms of periodic or impulsive noise. Both aspects are relevant to the acoustic treatment feasibility study of the 4 × 7-m Tunnel.

2.2 Geometrical Constraints

In an acoustic wind tunnel, the size and shape of the test chamber surrounding the free jet are important to the quality and type of acoustic measurements that can be made.

Figure 3(a) illustrates the geometrical constraints for out-of-flow far field acoustic measurements of scale model rotor noise in the test section of the 4 × 7-m Tunnel. It may be seen from figure 3(a) that it is only within limited vertical and horizontal arcs that out-of-flow far field acoustic measurements are possible. A solution to circumvent this limitation partially, however, is to relocate the tunnel control room outside the test chamber and to allow rotation of the model rotor plane about the tunnel centerline axis. (Models are usually tested with the rotor axis in a vertical plane only, as shown in fig. 3(a).) These combined measures would then allow almost complete hemispherical acoustic measurement coverage of the model with out-of-flow microphones. Rotor tip/boundary clearance is still considered adequate, and figure 3(b) also illustrates approximate floor clearance for a 2-m rotor operating in a vertical plane.

2.3 Background Noise Goal

It was pointed out earlier that both in-flow and out-of-flow microphone measurements are required for model rotor acoustic research in wind tunnels. To ensure that useful acoustic data are obtained from measurements, the maximum allowable tunnel background noise levels must be less than the source level to be measured for both in-flow and out-of-flow microphones. Tunnel background noise, which generally depends on the tunnel speed, is higher at higher tunnel speeds. Thus, an acoustic "design tunnel speed" must be selected in order to establish the background noise goal for the tunnel acoustic treatment. Based on the considerations of having both a high-enough tunnel speed for adequate rotorcraft system noise research and a low-enough tunnel speed for a low-risk and cost-effective acoustic treatment implementation, a tunnel speed of 120 knots was selected for this purpose.

From a preliminary evaluation of the source type and radiation characteristics of model scale helicopter rotors, it became apparent that the out-of-flow tunnel background noise requirement would be more stringent than the in-flow requirement. Therefore, the primary background noise goal to be considered in this study is that for out-of-flow measurement. (See fig. 4.)

The lower bound for in-flow background noise can be established based on the microphone self-noise predicted using the empirical method established in reference 18. (See also appendix G in ref. 13.) The empirical method was derived from measured microphone self-noise data obtained in a low-noise and low-turbulence (turbulence intensity less than 0.3 percent) quiet small-scale wind tunnel with careful consideration given to the microphone support to minimize support-generated noise. The lower bound of in-flow background noise is used as a reference to evaluate the quality of the tunnel acoustic treatment. For successful treatment, the tunnel-generated noise is expected to be lower than the lower bound.

The procedure for establishing the out-of-flow background noise goal (ref. 12) was based on calculated acoustic spectra from several important helicopter rotor source mechanisms at a distance of 5 m below the rotor hub along the rotor axis. The following source mechanisms were included in the calculation: high-speed impulsive noise, blade-vortex interaction noise, rotational noise, and broadband noise.

A 2-m-diameter two-blade rotor (NACA 0012 blade section) with a blade aspect ratio of 25 was used for all estimates at the acoustic design tunnel speed (120 knots). The two blade loadings used were 192 N/m^2 (4 lb/ft^2) and 766 N/m^2 (16 lb/ft^2), corresponding roughly to blade tip speeds of 152 m/sec (500 ft/sec) and 259 m/sec (850 ft/sec), respectively. An initial assessment of the relative magnitudes from the four source categories listed previously led to the conclusion that only broadband noise sources need to be considered in establishing the out-of-flow noise goal.

The broadband noise levels were computed using the prediction method proposed in reference 21, which includes turbulence ingestion (TI) noise, blade trailing-edge (TE) noise, and blade tip (TIP) noise. The prediction of TI noise was used as proposed, but the TE and TIP noise components were adjusted after a comparison with relevant experimental data. To accomplish this comparison, the measured two-dimensional (2-D) airfoil TE noise data reported in reference 22 were used to synthesize the rotor broadband noise by assuming that each spanwise section of the rotor blade behaves as an equivalent 2-D airfoil in the uniform local incoming flow. The contributions from blade sections were extrapolated using available data (ref. 22) and were added appropriately to give the broadband noise for the entire rotor. The comparison indicated that the synthesized rotor broadband noise was nominally 10 dB higher than the prediction (ref. 12). Thus, a 10-dB upward adjustment was applied to the prediction for TE noise. A similar adjustment was also made to TIP noise on account of the similarity of the physical mechanisms of the two types of noise, as postulated in reference 21. It is important to note that the crude comparison made in this study by no means represents a validation of the prediction method proposed in reference 21. This was considered the best approach possible at this time in the absence of any definitive data on rotor broadband noise from a well-controlled experiment. (The lack of rotor broadband noise data is due largely to the lack of a suitable test facility.)

The adjusted TE, TIP, and TI levels were then added logarithmically to produce a total rotor broadband noise for the two assumed blade loading levels. To account for the decrease in broadband off-axis radiation at 30° from the rotor axis, 6 dB were subtracted (assuming dipole directivity) from these totals. An out-of-flow background noise goal was obtained by taking the arithmetic average of the broadband noise levels for the two blade loadings.

Figure 4 gives a comparison of the out-of-flow design-goal noise level and the lower bound on in-flow background noise with the existing in-flow and out-of-flow background noise levels at the acoustic design tunnel speed. It is seen that the minimum tunnel background noise reduction required ranges from 37 dB at 100 Hz to 5 dB at 8 kHz for out-of-flow measurement. The in-flow background noise is about 15 to 20 dB higher than the lower bound for microphone self-noise.

2.4 Quantification of Acoustic Sources and Paths

In order to determine methods for achieving the required tunnel background noise reduction, detailed quantitative information regarding acoustic sources and noise propagation paths was required.

Source/path data were provided through an extensive measurement and analysis study performed in reference 13. The objective of this study was to diagnose the contributing sources to the background noise in the test section/test chamber and the paths by which the background noise reaches the test section/test chamber. Principal results of this study are summarized in the following discussion.

The major background noise sources determined from the measurements described in reference 13 are depicted schematically in figure 5. Estimated 1/3-octave-band acoustic power levels for the two dominant sources, namely, the tunnel drive fan and first- and second-corner turning vanes, for three tunnel speeds (40, 80, and 160 knots) are shown in figure 6. Acoustic attenuation due to propagation from various source locations to the test section is shown in figure 7. Steps to attenuate the machinery noise noted in figure 6 have already taken place since the time that these measurements were made by relocating an oil pump outside the tunnel circuit.

The total measured background noise spectrum in the test section together with an estimation of its constituent parts are presented in figure 8. It may be seen from these results that the fan noise propagation via the upstream path is dominant, with nearly equal contributions at low frequencies from fan noise propagating via the downstream path. Turning vane noise is seen to be less important; however, the authors of reference 13 note that the turning vane noise calculation may be subject to error - possibly 10 dB - because of a lack of necessary detailed information regarding the flow field incident upon the vane set.

2.5 Options for Reduction of Test Chamber Noise

In a subsequent study (ref. 14), options for reducing the test chamber background noise level to meet the NASA goal were defined and evaluated. This analysis was based on a detailed examination of the measured results, the maximum acceptable tunnel background noise criterion previously established, and good practice in wind-tunnel noise control. The following four noise-reduction options were identified in reference 14 to achieve the acoustic objectives for the upgrade of the Langley 4- by 7-Meter Tunnel:

Option	Description
I	Retain the current fan and tunnel circuit, but reduce test section size with a smaller nozzle.
II	Retain the current fan, but add extensive acoustic treatment to the tunnel circuit.
III	Rebuild only the fan to reduce blade loading and improve efficiency.
IV	Rebuild the fan and add necessary treatment to the circuit.

The impact of these options given in reference 14 is summarized in table I.

Although the author of reference 14 conducted a technical evaluation and relative cost/benefit analysis (table I) of the four noise reduction options previously summarized, two additional criteria to those used by him are required in evaluating the relative merits of the available options: (a) an acceptable level of confidence in achieving the necessary noise reduction, and (b) no degradation in aerodynamic performance of the tunnel.

From this perspective, option IV was identified as the only one capable of meeting both the background noise goal and the additional criteria. Some of the reasoning leading to this conclusion is given as follows:

Option I was considered attractive initially, especially from a cost viewpoint. Additional analysis, however, revealed that the reduction in nozzle size would not only compromise the model size requirement but also present serious concern on the performance of the first diffuser. The performance of the present nozzle and first diffuser was evaluated in reference 23.

Option II relies heavily on the use of acoustic absorbing devices placed around the tunnel circuit. It represents a passive approach to the noise reduction problem. It is likely that the additional aerodynamic losses associated with these acoustic absorbing devices, particularly those placed in the high-velocity region of the tunnel, and the self-noise generation from these devices themselves will offset some of the overall noise reduction.

Option III represents a direct approach to noise reduction - that is, reduction of noise at the source. It is the most desirable approach since methods for fan noise reduction at the source are relatively well established (ref. 24). Techniques such as tip speed reduction, blade loading optimization, and optimized matching of the fan design to the tunnel in-flow are known to provide reliable fan noise reduction. However, based on the estimates provided in reference 14 and consideration of the current fan design practice, it was concluded, however, that the required noise reduction cannot be achieved by rebuilding the existing fan alone.

Thus, after careful evaluation of all the available options, option IV shown in figure 9 was selected as the only one that involves an acceptable level of risk and has minimum detrimental impact on the aerodynamic performance of the tunnel. (In fact, the possibility exists that fan redesign may provide an improvement in the aerodynamic performance of the tunnel.) The essential features of the chosen option IV were as follows:

1. A 50-percent speed reduction of the tunnel drive fan (93 rpm at acoustic design tunnel speed)

2. Fan reblading to maximize the aerodynamic efficiency of the fan and to provide an improved matching between the fan and tunnel circuit flow

3. A minimum amount of acoustic treatment inside the tunnel circuit to ensure low losses and self-noise generation due to treatment

4. Relocation of the present control room outside the test chamber

5. Acoustic treatment of all test chamber surfaces to ensure a high-quality acoustic measurement environment.

3 ENGINEERING FEASIBILITY STUDY

After determining a desirable option for acoustic treatment of the 4 × 7-m Tunnel, a study was conducted to assess the engineering feasibility of satisfactorily implementing this option.

One of the critical questions to be resolved in the engineering feasibility study was the fan redesign to achieve a 50-percent speed reduction while maintaining the present tunnel flow capability at improved aerodynamic efficiency.

The engineering feasibility study is summarized in reference 16. At the conclusion of this study, it was apparent that the required 50-percent fan speed reduction is incompatible with conventional practice in wind-tunnel drive fan design. Without compromising any of the tunnel performance constraints, the achievable fan speed reduction is conservatively estimated to be 27 percent (135 rpm at acoustic tunnel design speed). This 27-percent fan speed reduction implies that the required background noise reduction due to fan speed would fall short of the design goal by 8 dB.

The main features of the redesigned fan included (1) a blade profile consisting of a wide-chord NACA 65-series airfoil with circular-arc camber, a hub solidity of 2, and a tip-to-hub chord ratio of 0.75; (2) an increase in the blade number from 9 to 19; (3) an increase in the hub diameter from 4.9 to 7 m with a new nose cone; (4) an addition of five inlet guide vanes to provide a 30° prewhirl; and (5) an increase in the tail cone length.

The findings presented in reference 16 showed the need for a reevaluation of the elements of the selected treatment option and an effort to contrast the present acoustic treatment approach of the 4 × 7-m Tunnel with the design features of the DNW. This integrated analysis is presented in the following section.

4 REVIEW AND INTEGRATED ANALYSIS OF STUDY COMPONENTS

At the conclusion of the engineering feasibility study, a renewed effort was initiated to review critically the various elements in the selected option so that the treatment feasibility issue could be addressed. The various activities conducted are summarized in this section.

4.1 Comparison of Background Noise Between 4 × 7-m and DNW Tunnels

The DNW tunnel was designed and constructed with aeroacoustic testing in mind and, as such, it is generally considered the best large-scale aeroacoustic testing facility worldwide. A comparison of measured tunnel background noise levels for the 4 × 7-m Tunnel with those of the DNW should therefore be instructive in assessing the acoustic treatment required for the 4 × 7-m Tunnel. Figure 10 shows such a comparison. (Throughout this report DNW measurements at 65 m/sec have been used for comparisons with the 4 × 7-m Tunnel at 120 knots.)

It is seen that the difference in the background levels between in-flow and out-of-flow noise for the 4 × 7-m Tunnel is about 5 dB over the entire spectral range. The corresponding difference for the DNW is in the range from 20 to 25 dB for the entire spectral range and is substantially higher than that observed for the 4 × 7-m Tunnel. One of the major differences between the two tunnels is the test chamber acoustic environment; that is, the test chamber of the DNW is anechoic and the test chamber for the 4 × 7-m Tunnel is semireverberant.

It is also pertinent to note that the in-flow background noise levels of the two tunnels are generally comparable. This contrasts dramatically with the large difference between their out-of-flow levels. Furthermore, the out-of-flow background noise level measured for the 4 × 7-m Tunnel is insensitive to the microphone location (ref. 13); whereas for the DNW, the background noise level reduces as the out-of-flow distance to the tunnel centerline is increased (ref. 10). These observed differences motivated a study (ref. 15) to investigate the major contributing factor to the large noise reduction in out-of-flow background noise level that existed in the DNW. The findings of this study are summarized in the next section.

It is also pertinent to note that in making the comparison shown in figure 10, no consideration was given to the scaling aspects of the two tunnels. For instance, the nozzle size for the DNW is 6 m by 8 m, which is about 1.7 times larger than that of the 4 × 7-m Tunnel, and the test chamber volume is much greater for the DNW.

4.2 Effect of Test Chamber Acoustic Treatment on Out-of-Flow Noise

In reference 13 the reduction of out-of-flow background noise due to acoustic treatment of the test chamber was originally estimated to be between 5 and 10 dB. This estimate was based on the measured directivity of tunnel noise radiating into the open test section from the first diffuser and the reduction of test chamber reverberation. To substantiate this estimate as well as to understand the difference between in-flow and out-of-flow background noise levels observed for the DNW (see fig. 10), a computational study was performed and is reported in reference 15. This study involved a 2-D modeling of the nozzle, the test chamber, and the first diffuser of the tunnel circuit to assess the effect of acoustically absorbent treatment of test chamber surfaces on the sound field in the test chamber. The geometry of the portion of the tunnel circuit modeled in the analysis is shown in figure 11.

Typical results at low frequencies are shown in figure 12. It is seen that the test chamber treatment resulted in noise levels at typical out-of-flow microphone locations (near the chamber wall) some 20 to 25 dB lower than the in-flow noise level. Additional computation with tunnel flow included showed a similar trend. (See ref. 15.)

It thus appears that the original estimate (ref. 13) on the out-of-flow noise reduction due to acoustic treatment of the test chamber was too conservative. To verify further the computed results of reference 15, the computed results were compared with the difference in background noise levels measured in the DNW. The difference between the DNW in-flow and out-of-flow background noise levels as shown in figure 10 is plotted in figure 13. A noise reduction from 18 to 32 dB is evident over the entire frequency range of interest. This noise reduction is believed to be due to the acoustic treatment of the test chamber.[2]

If it is conservatively assumed from the DNW data that a nominal reduction of 20 dB is due to test chamber treatment alone, the magnitude of the noise reduction

[2]This view is shared by the DNW personnel (J. C. A. van Ditshuizen) through private communication.

observed in the DNW can be extrapolated to the 4 × 7-m Tunnel situation once a distance scaling law is established. Using the out-of-flow noise directivity data measured by the DNW (ref. 10) at sideline distances of 8.6 and 12.2 m, it was established that the distance scaling follows an approximate inverse square law in terms of r/D^*, where r is the sideline distance and D^* is the equivalent nozzle diameter. (See fig. 14.)

For the 4 × 7-m Tunnel, as in section 2, this study assumed a 2-m-diameter model rotor with the out-of-flow noise measurements being made at 2.5 rotor diameters (5 m) away from the model centerline. This gives an r/D^* of 0.94 resulting in a reduction of 13 dB for out-of-flow background noise if one assumes that the trend observed for out-of-flow background noise reduction in the DNW is applicable to the 4 × 7-m Tunnel. The corresponding results obtained from an analysis made at low frequency are also plotted in the same figure for comparison. It is seen that the predicted values generally exceed the conservative representation of the DNW data.

4.3 Noise Reduction Due to Fan Redesign

The noise reduction due to achievable fan speed reduction (27 percent) alone can be readily estimated using the noise scaling law as established in reference 13. The spectrum of the tunnel background noise with a rebuilt drive fan operating with a 27-percent speed reduction will be 5 dB lower than the present background noise with the entire spectrum shifted to the lower end by 1/3 octave. An additional 8-dB noise reduction, as estimated in reference 13, due to improved fan aerodynamic flow is also applied. The overall effect of a rebuilt fan on the out-of-flow tunnel background noise calculated in this manner is shown in figure 15. It is seen that the out-of-flow noise goal is met for frequencies greater than 1 kHz. The additional reduction required below 1 kHz is still substantial. Figure 16 shows the effect of a rebuilt fan on in-flow background noise. It is seen that the in-flow background noise level approaches the lower bound for microphone self-noise. In fact, if only in-flow measurement is of interest, based on the discussion made in relation to figure 2 regarding the source type suitable for in-flow measurement, there would be no need to reduce further the in-flow background noise.

Additional effort was expended in the attempt to estimate independently the noise reduction due to fan aerodynamic flow improvement. Referring to figure 10, it was pointed out in the discussion that the in-flow noise level in the DNW is only marginally lower than that in the 4 × 7-m Tunnel at corresponding tunnel speeds. This observation was surprising since it has been reported (ref. 11) that great care was taken in the acoustic design of the DNW fan.

Further study on this aspect, however, has revealed that a direct comparison, as was presented in figure 10, can be misleading. This is because noise radiation from wind-tunnel fans depends on many design and operating parameters such as fan tip speed, mechanical power delivered, aerodynamic efficiency, and blade loading distribution. Also, the incoming flow to the fan is important. The state of incoming flow in turn depends on the aerodynamic performance of the tunnel circuit as a whole. In comparing noise radiation from wind-tunnel fans of different designs, consideration must be given to all the parameters previously stated. The DNW fan has a higher aerodynamic efficiency than that estimated for the present 4 × 7-m Tunnel fan. The mechanical power delivered to the open test section by the DNW fan is about twice that of the 4 × 7-m Tunnel. The design tip speed of the DNW fan, however, is only 80 percent of that for the 4 × 7-m Tunnel. The DNW fan and tunnel circuit are similar in size to those of the 4 × 7-m Tunnel (fan diameters are 12.5 m and 12.3 m for the DNW and the 4 × 7-m Tunnel, respectively), but the test section size of the DNW is 1.7 times larger. (The DNW test section is 6 m by 8 m.)

Using the fact that circuit sizes and layouts of the two tunnels are roughly similar, an attempt was made to evaluate (from known aerodynamic and acoustic data of the two tunnels) the noise level that a fan similar to the DNW design would produce if it were installed in the 4 × 7-m Tunnel. The aim of this exercise was to verify independently the 8-dB noise benefit estimated in reference 13 due to the redesign of the 4 × 7-m Tunnel fan. The approach taken was to size the DNW fan to meet the 4 × 7-m Tunnel flow requirement at the performance point selected for the acoustic design condition (120 knots) and then to calculate the noise radiation of this fan based on published noise data of the DNW fan. This attempt was unsuccessful because of the large number of variables involved in this calculation and the unavailability of both noise and performance data of the DNW fan at off-design conditions.

It is pertinent to point out that for large-scale industrial fans used in cooling towers and air-fin coolers, reference 24 notes that a noise reduction of 15 dB or more has been achieved for the same airflow with more efficient wide-blade low-speed fans than the previous narrow-blade high tip speed fans. The same approach was used in the engineering feasibility study for a new fan design described in reference 16 and in section 3 of this report.

However, because an independent verification on the calculation in reference 13 was not possible, and because of the importance of the estimate, it is recommended that the estimated 8-dB noise reduction due to improved fan aerodynamic flow should be verified by model scale testing.

4.4 Reassessment of Acoustic Treatment Required To Achieve Out-of-Flow Noise Goal

With the reevaluation of noise reduction achievable with a rebuilt fan (27-percent speed reduction) and the understanding gained on the effect of an anechoic test chamber on out-of-flow background noise, a reassessment of the treatment approach to achieve the tunnel background noise goal was made. Figure 17 shows the anticipated out-of-flow noise reduction due to acoustic treatment of the test chamber for the rebuilt fan. The additional noise reduction illustrated was obtained from the estimate made in figure 13 and was applied uniformly over the entire spectrum. It is seen that the out-of-flow noise goal is satisfied for frequencies above 500 Hz. The remaining reduction required at low frequencies for meeting the goal is reduced to about 10 dB, as shown by comparing figure 17 with figure 15. For in-flow background noise, it is assumed conservatively that the acoustic treatment of the test chamber contributes no reduction.

The remaining noise reduction required to satisfy the out-of-flow background noise goal is obtained by treating critical parts of the tunnel circuit. The treatment approach initially proposed in reference 13 (see fig. 9) was carefully analyzed together with additional considerations given to the cost effectiveness and elimination of possible reflections of axially propagating test model noise from the first- and fourth-corner turning vanes (which are along the line of sight of the model). The analysis indicated that the first- and fourth-corner turning vanes should be acoustically treated.

To estimate the effect of acoustic treatment for corner turning vanes on out-of-flow tunnel background noise, the predicted out-of-flow noise with the rebuilt fan (see figs. 15 and 16) was separated into upstream and downstream contributions from the fan using the propagation attenuation data shown in figure 7. The contribution to the test section noise due to turning vanes was omitted in the calculation since the turning vane noise is estimated to be at least 10 dB lower than the fan noise. (See fig. 8.) Figure 18 shows the attenuation achievable with acoustic treatment for the first-corner turning vane on the upstream contribution to the out-of-flow background noise. A corresponding result with treatment for the fourth-corner turning vane is given in figure 19. The insertion loss for the acoustically treated corner vanes was estimated based on the data available in references 13 and 16. The combined effect of acoustic treatment for the first- and fourth-corner turning vanes is obtained by logarithmically adding the upstream and downstream contributions. The result is shown in figure 20. It is seen that the out-of-flow background noise goal is satisfied at all but the lowest frequency (100 Hz). Further assessment of this discrepancy revealed that it will not compromise the original objective for rotorcraft acoustic testing, because the weaker source mechanism of interest at this frequency is atmospheric turbulent ingestion noise that may not be realistically simulated in a wind tunnel.

The corresponding result for the in-flow background noise with acoustic treatment for the first- and fourth-corner turning vanes is shown in figure 21. It is seen that the in-flow background noise achievable is actually lower than the lower bound for microphone self-noise.

4.5 Acoustic Treatment of Test Chamber Floor

The initial approach examined in the engineering feasibility study (ref. 16) for acoustic treatment of the test chamber floor consisted of a portable 2-ft-flat acoustic treatment placed on the existing floor during an acoustic test. This treatment decreases the model-to-floor clearance, which is of concern from the point of view of acoustic testing since full directivity measurements require model rotation, and adequate model-to-tunnel floor clearance is important from both aerodynamic and acoustic considerations.

Additionally, turbulence along the floor of the first diffuser from the termination of the acoustic floor treatment may be expected to reduce the quality of the flow throughout the tunnel.

An alternative method of acoustic treatment that would avoid these problems would be to recess the treatment below the existing tunnel floor.

CONCLUDING REMARKS

This report, which has summarized the acoustic treatment feasibility study for the Langley 4- by 7-Meter Tunnel, has determined that modification of the tunnel for rotorcraft noise research is feasible. The NASA design noise goal summarized in this report can be achieved by introducing the following modifications:

- A rebuilt fan operating at 135 rpm or below
- Acoustic treatment of the test chamber
- Treating the first-corner turning vane set
- Treating the fourth-corner turning vane set

It is recommended, however, that model tests be conducted to verify the aerodynamic performance and noise reduction benefit because of fan reblading and aerodynamic efficiency improvements. Also, concepts for tunnel floor acoustic treatment should be further evaluated.

In addition to providing a sound basis for the aforementioned conclusions, the study described in this report sheds new light on the design of an acoustic wind tunnel. When taken in aggregate with the cited references, it is also considered that this report demonstrates a procedure that could be applied to other feasibility studies for wind-tunnel acoustic treatment.

NASA Langley Research Center
Hampton, VA 23665-5225
April 29, 1986

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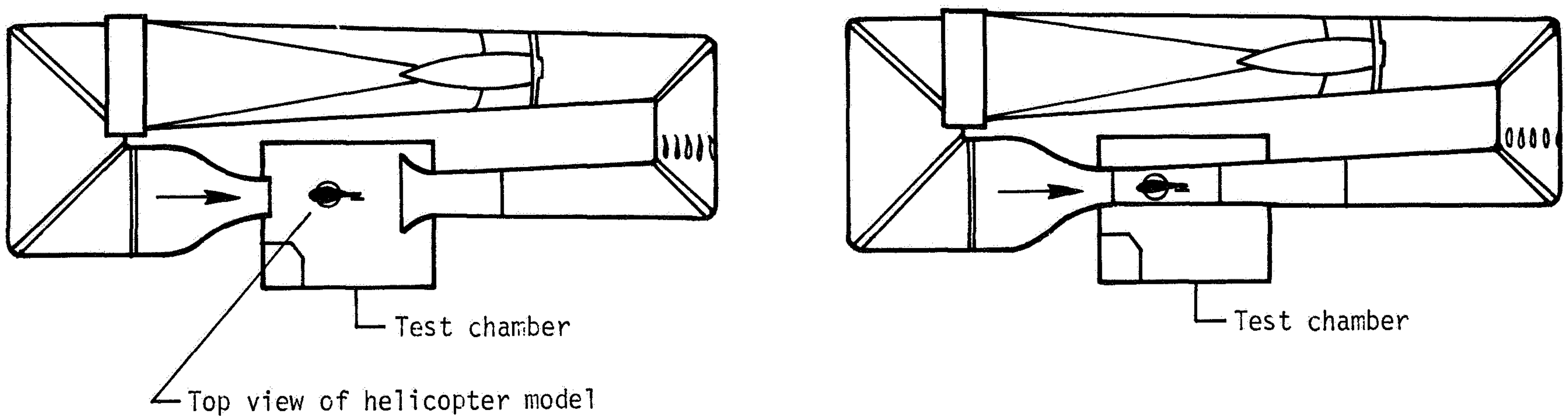
TABLE I.- IMPACT OF FOUR NOISE-REDUCTION OPTIONS ON THE LANGLEY 4- BY 7-METER TUNNEL

[Data taken from reference 14]

Noise reduction option (a)	Impact on facility capabilities and operations for -									
	Background noise goal	Model size limit / Minimum acceptable	Model size limit / Current maximum	Flow quality / Planned flow quality	Maximum q_0 / Current maximum q_0 (b)	Relative initial cost	Relative operative cost (b)	Maintenance required	Downtime for conversion	Additional steps needed
I Retain current fan, etc.; test with smaller nozzles	Can meet	Can meet (pending verification)	Limited to ≈0.5	Improves because of increased contraction	Same (or higher)	Low	Reduced power requirements	Storage of nozzles	Virtually none	• Verify aero assumptions • Verify fan noise reduction • Design • Procure
II Retain current fan and add acoustic treatment to circuit	Can meet or exceed	Exceeds	None	Possible minor degradation (or minor improvement)	May reduce by 8 to 10%	High	Increase $\propto \Delta q/q_0$	Periodic cleaning of certain treatment	Substantial (to be determined)	• Model tests • Design • Procurement
III Rebuild fan	Probably can't meet without some treatment in circuit	Exceeds	None	Could improve	Could increase	High	Below current costs	Probably below current levels	Substantial (to be determined)	• Model tests • Full-scale flow measurements • Design • Model test • Procurement
IV Rebuild fan and add acoustic treatment to circuit	Could exceed goals by large margin	Exceeds	None	Could improve	Could increase	High	Below current costs	Fan: Less than current Treatment: Periodic cleaning	Substantial (take longest of II or III)	II + III

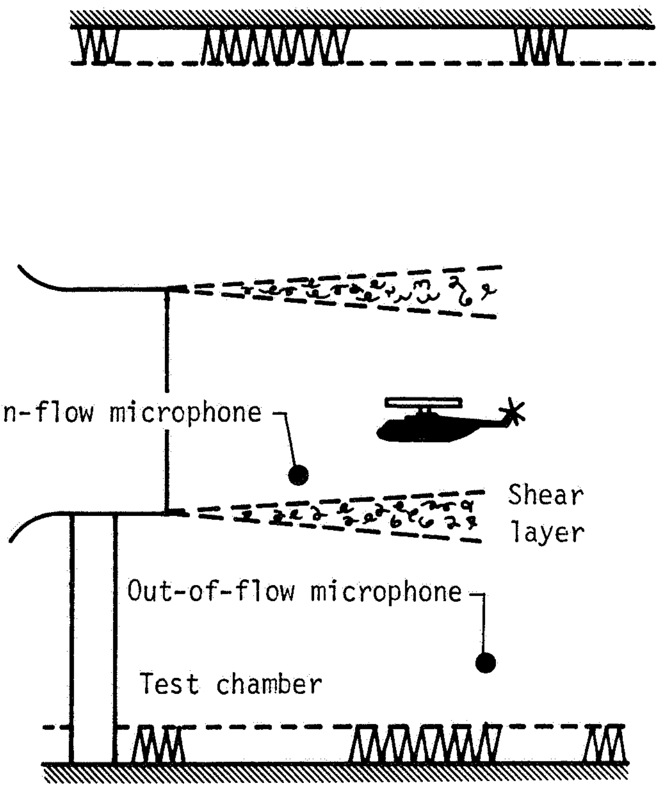
[a]All options assume that suitable acoustic treatment will be installed in the test section and that the current control room will be relocated outside the test chamber.
[b]The symbol q_0 denotes the nominal wind-tunnel dynamic pressure, and Δq denotes the change in q_0.



(a) Open test section mode.

(b) Closed test section mode.

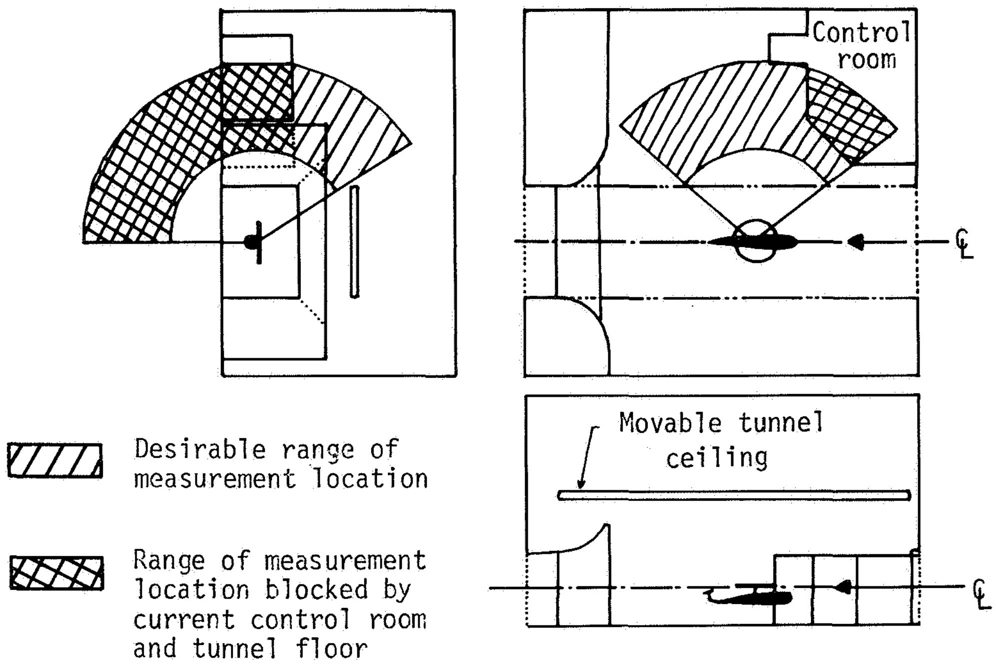
Figure 1.- Schematic drawing of the Langley 4- by 7-Meter Tunnel showing modes of operation.



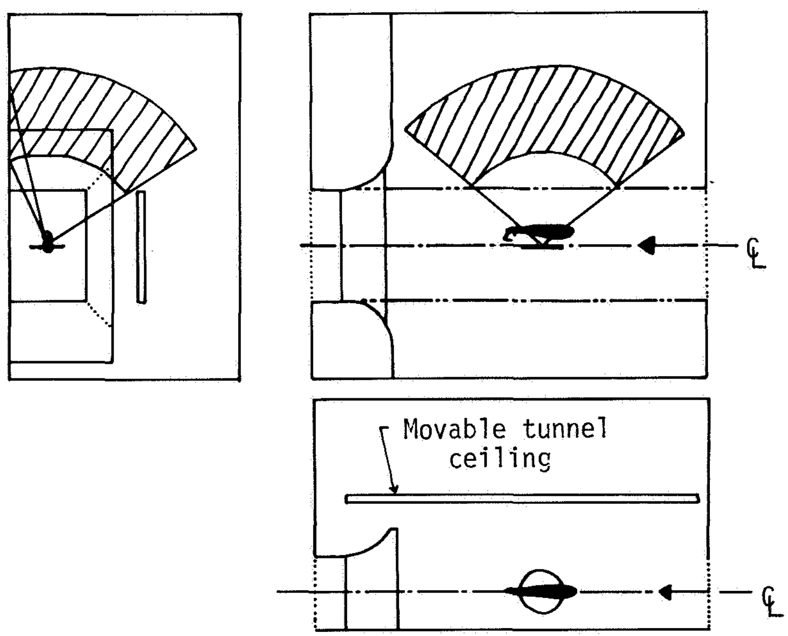
Description	In-flow microphone	Out-of-flow microphone
Background noise	High	Low
Microphone wind noise	Yes	No
Microphone support noise	Yes	No
Far field measurement	Some directions	All directions
Signal-to-noise ratio:		
Periodic source	Adequate	High
Random source	Inadequate	Adequate
Shear layer correction (spectrum):		
Periodic source	Not needed	(a)
Random source	Not needed	Reliable
Waveform distortion:		
Periodic source	No	Moderate to severe
Random source	Not applicable	Not applicable

[a]Reliable to moderately high frequencies.

Figure 2.- Microphone placement trade-offs for rotor noise measurement in a free-jet acoustic wind tunnel.



(a) Model position for normal operation showing blockage of measurement location by current control room and tunnel floor.



(b) Typical model position for sideway operation with control room relocated outside test chamber showing increase in measurement range.

Figure 3.- Schematic drawing showing open test section and test chamber.

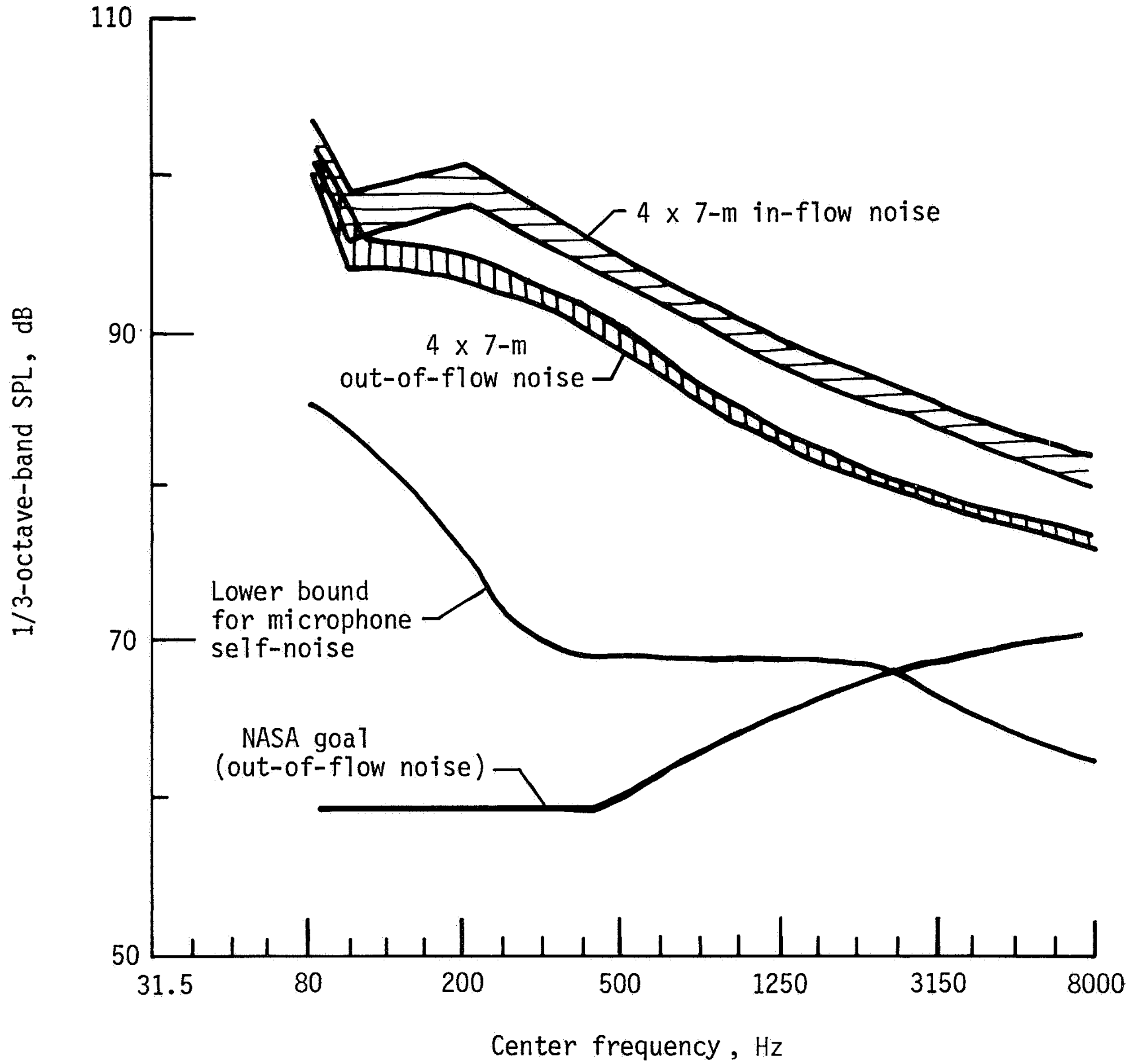


Figure 4.- Comparison of measured background noise levels of the 4 × 7-m Tunnel with NASA design noise goal. Tunnel speed, 120 knots.

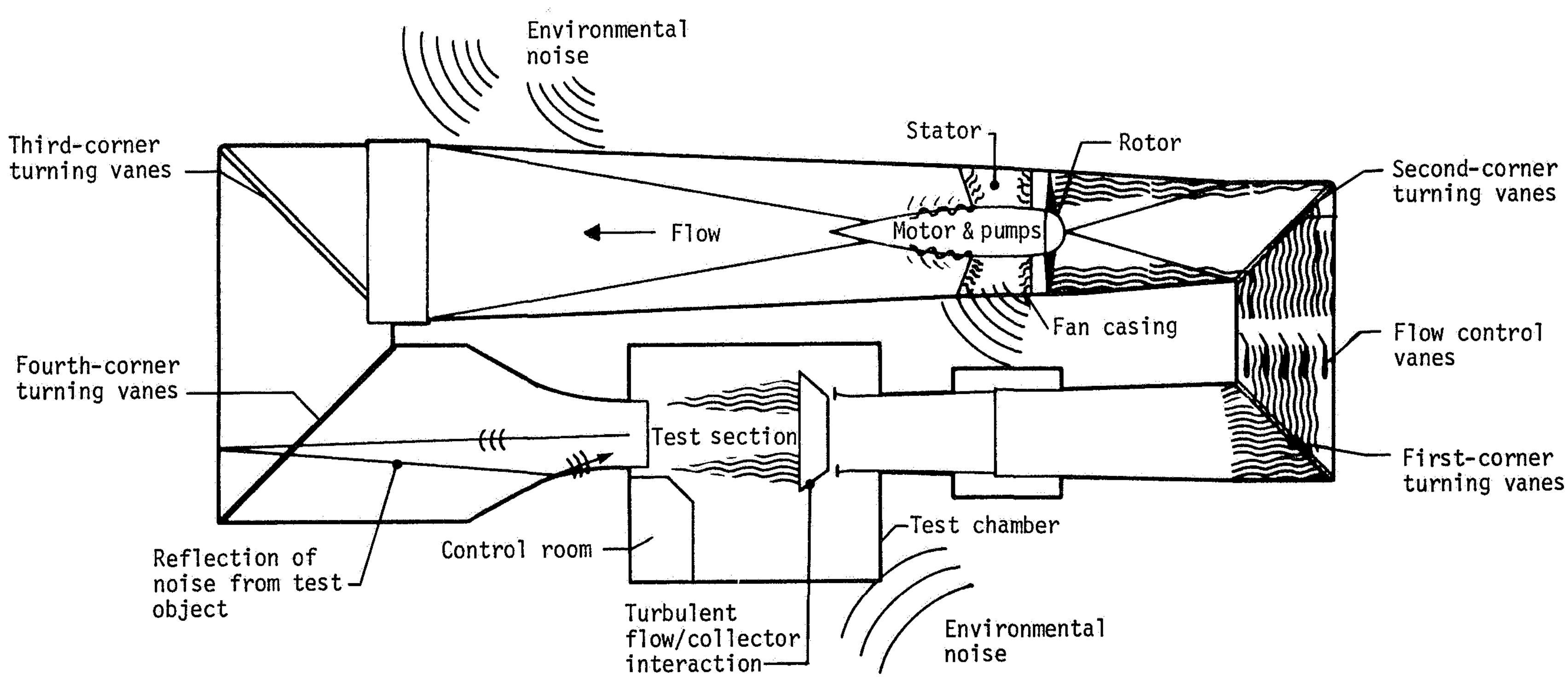


Figure 5.- Schematic drawing showing noise sources in the 4 × 7-m Tunnel. Figure taken from reference 13.

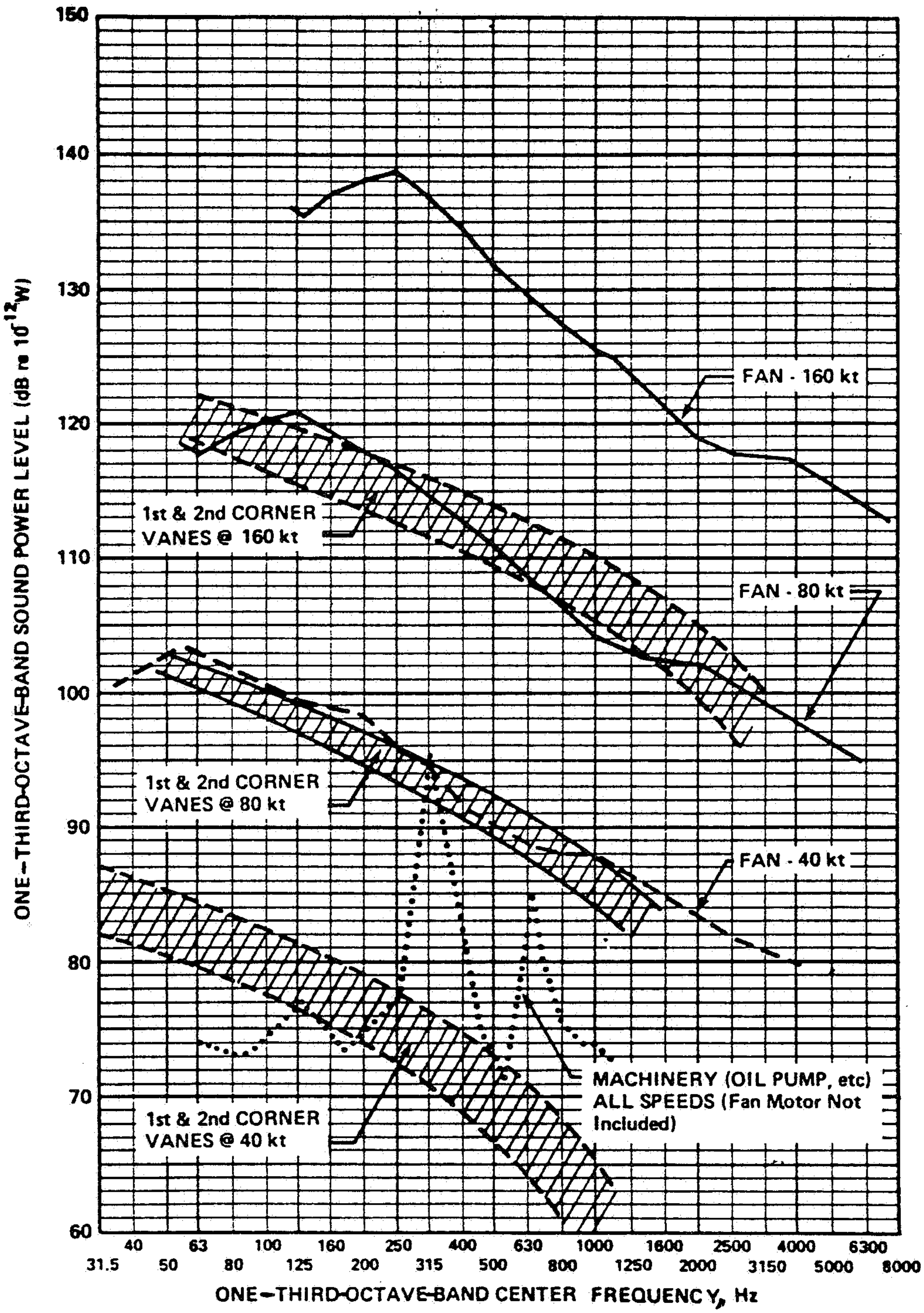


Figure 6.- Estimated sound power level of fan and turning vanes. Figure taken from reference 13.

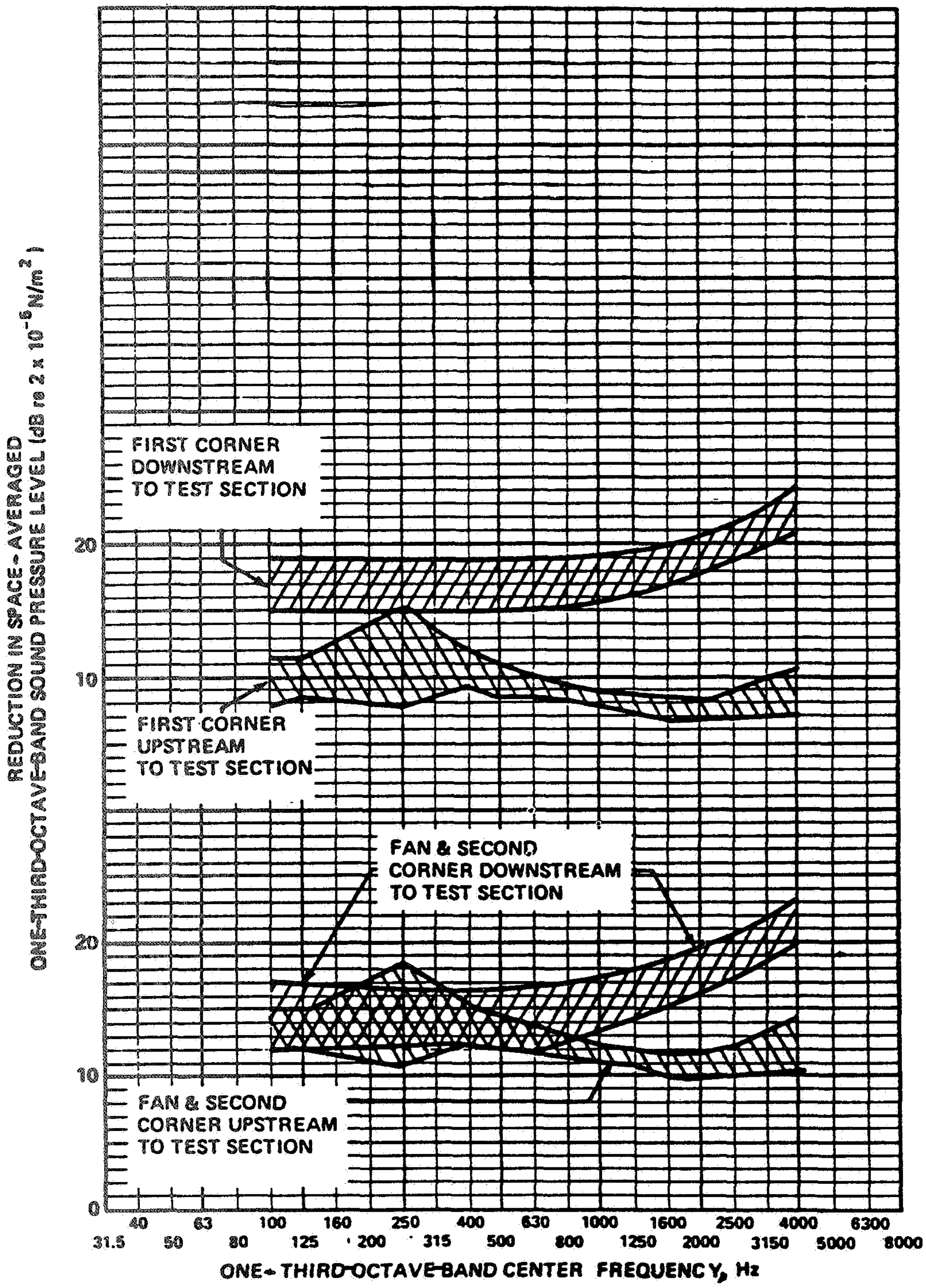


Figure 7.- Estimated reduction in sound pressure level between various source locations and test section. Figure taken from reference 13.

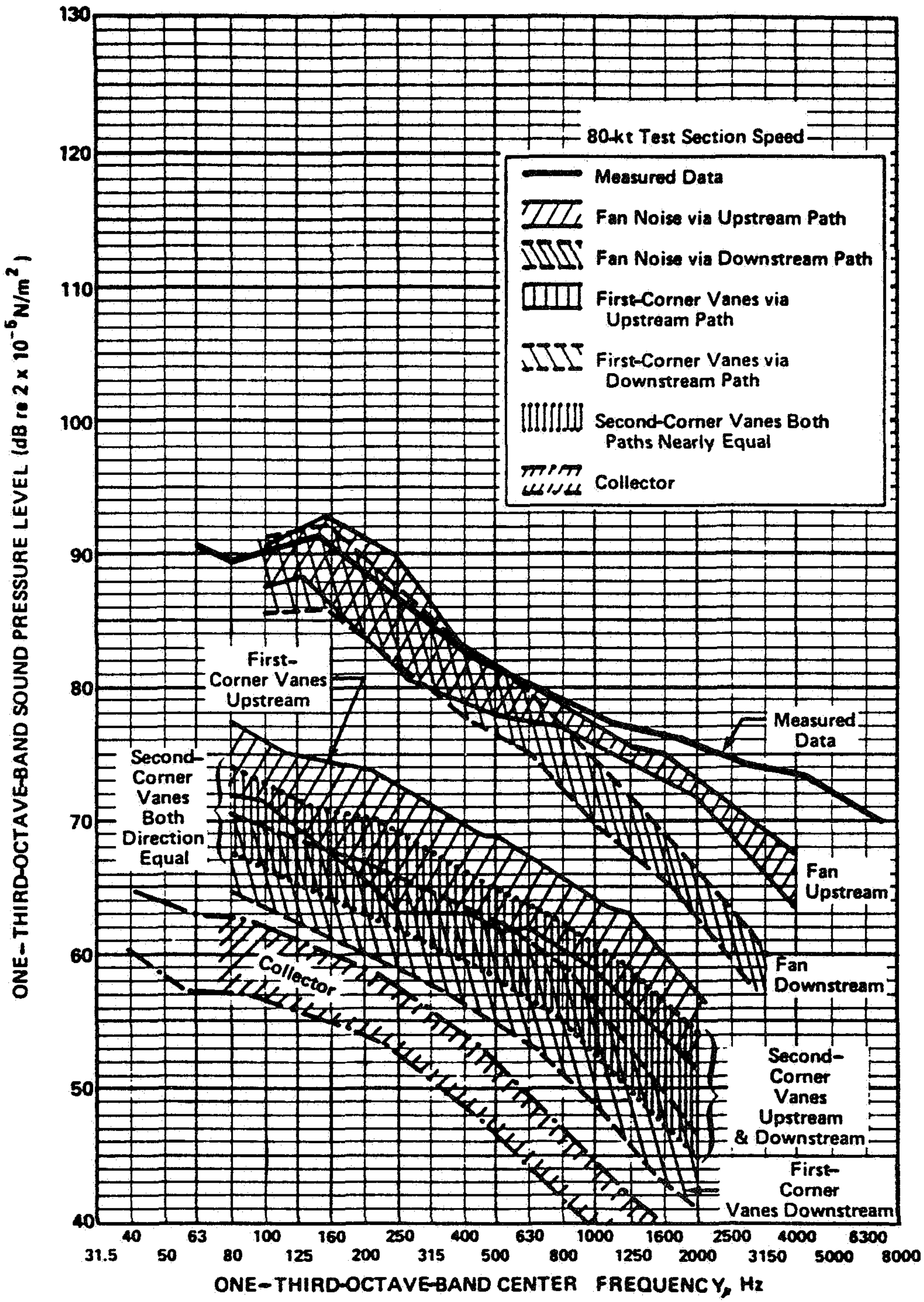


Figure 8.- Estimated source/path constituents of measured in-flow background noise level at 80-knot test section speed. Figure taken from reference 13. Same relative levels expected at 120 knots.

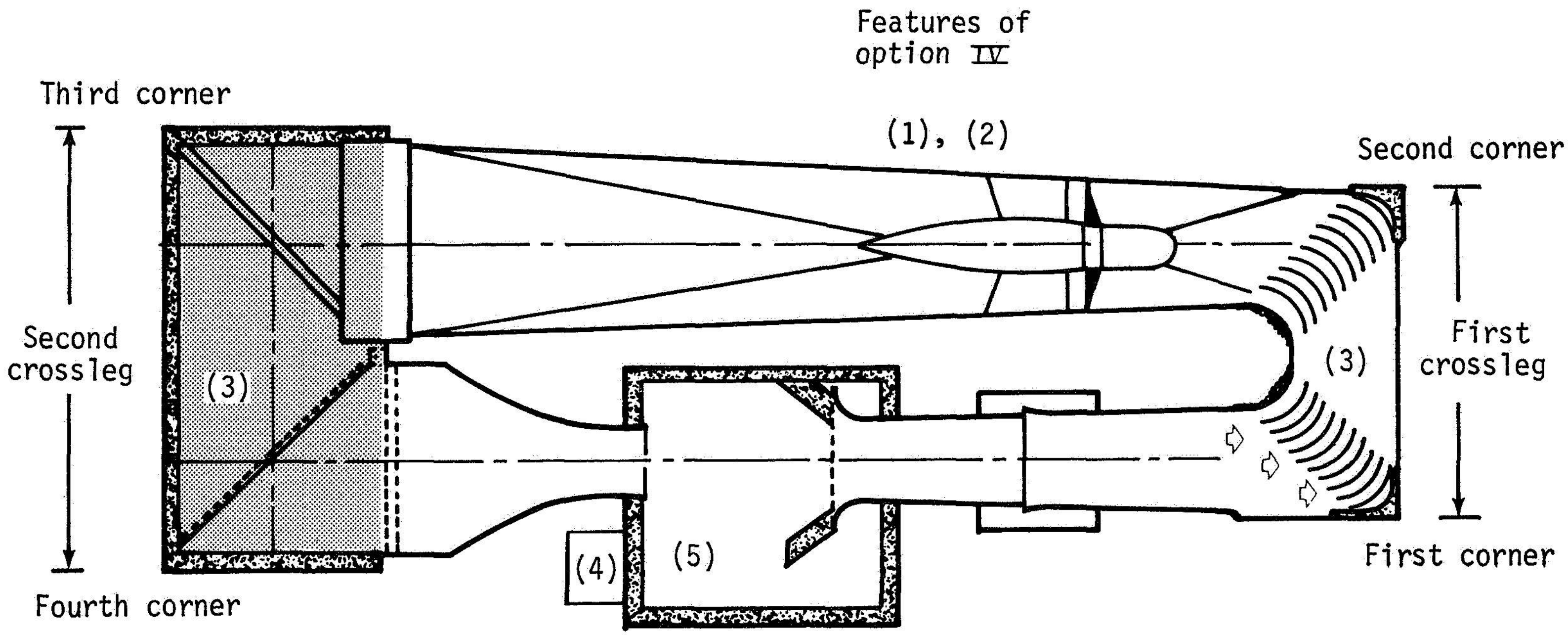


Figure 9.- Essential features of option IV for tunnel acoustic treatment selected for meeting initial noise goal.

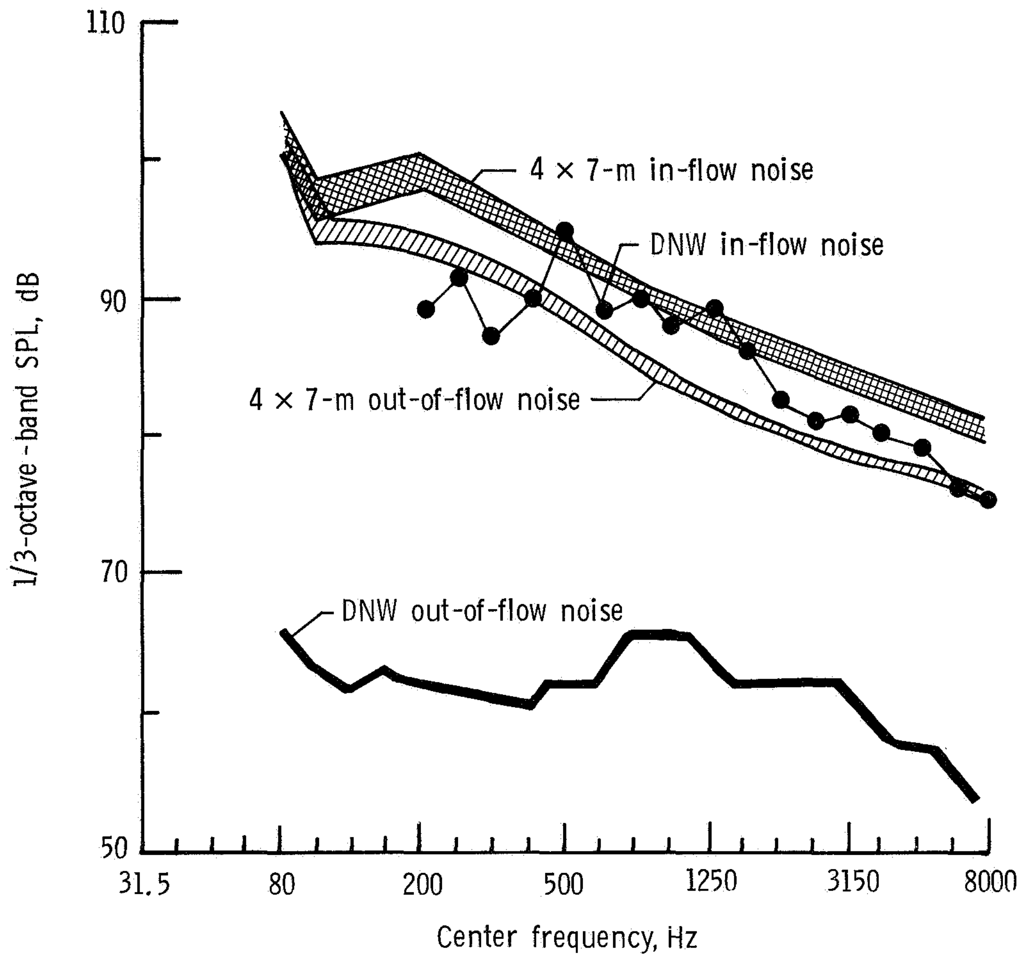


Figure 10.- Comparison of measured background noise levels between the 4 × 7-m Tunnel and the DNW. Tunnel speed, 120 knots.

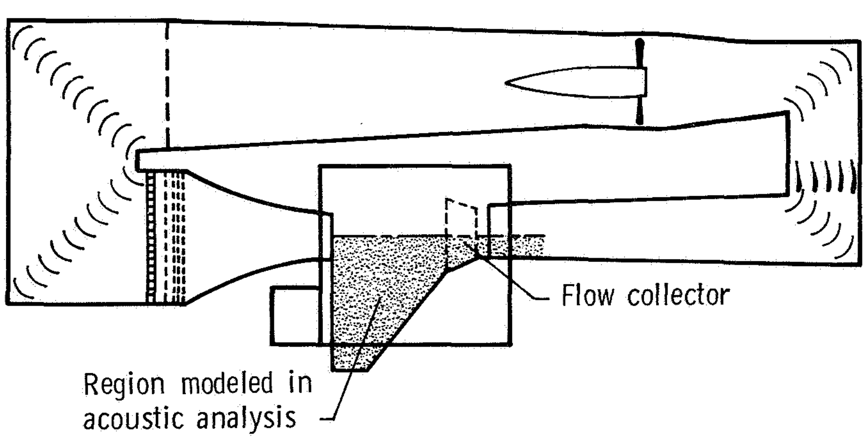


Figure 11.- Schematic drawing of the 4 × 7-m Tunnel showing portion of tunnel circuit modeled in acoustic analysis.

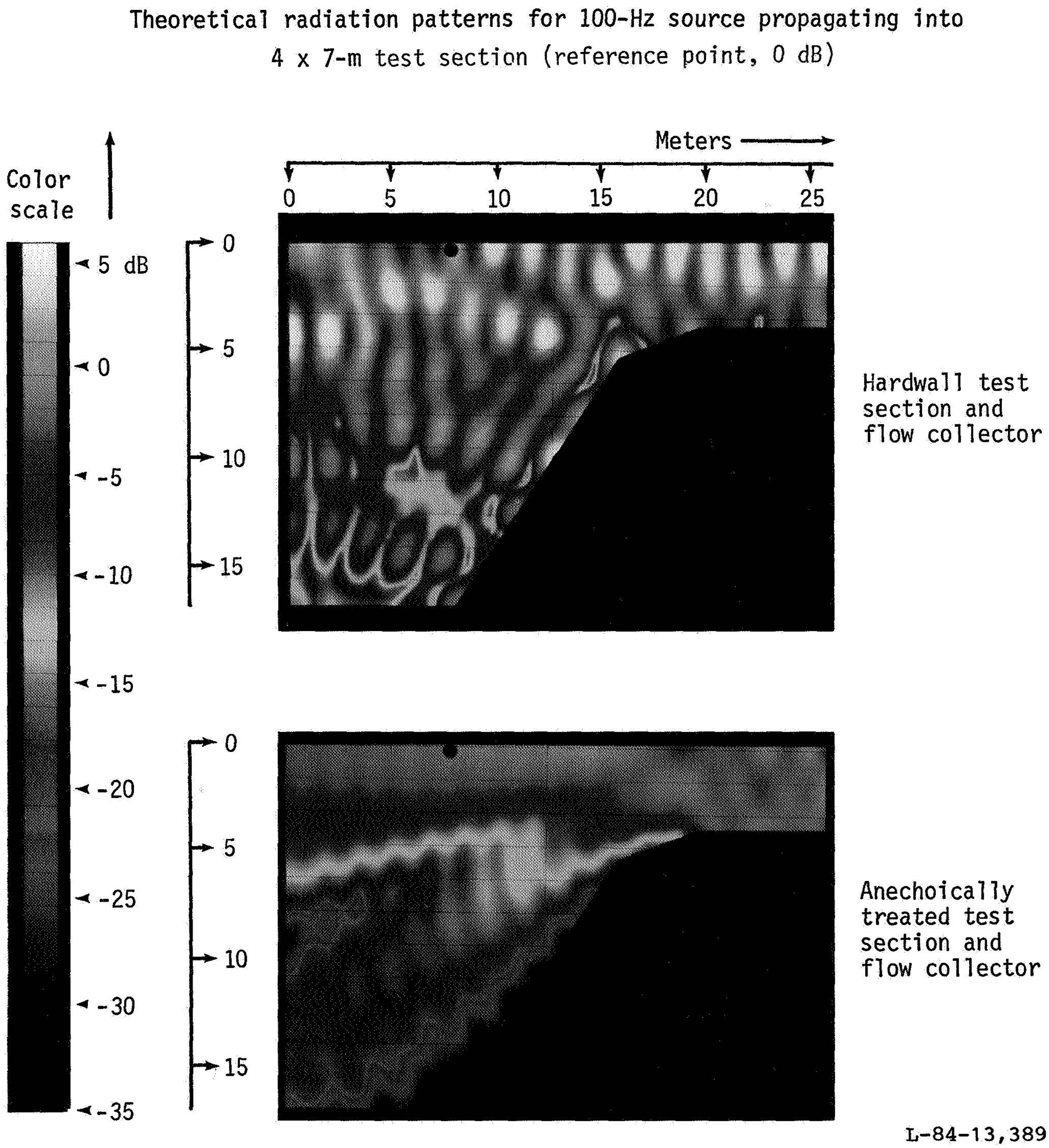


Figure 12.- Computed sound field throughout tunnel test section showing effect of anechoic treatment of test chamber.

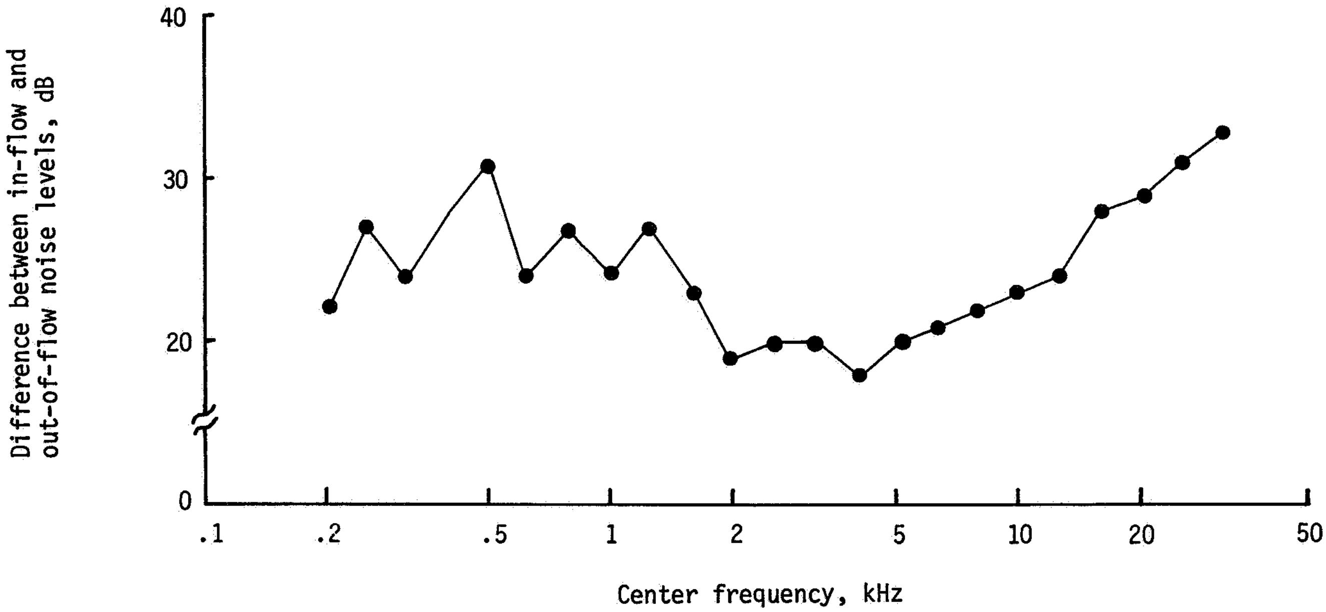


Figure 13.- Difference between in-flow and out-of-flow background noise levels of the DNW showing effect of test chamber acoustic treatment. Tunnel speed, 120 knots; out-of-flow microphone 12.2 m from tunnel centerline.

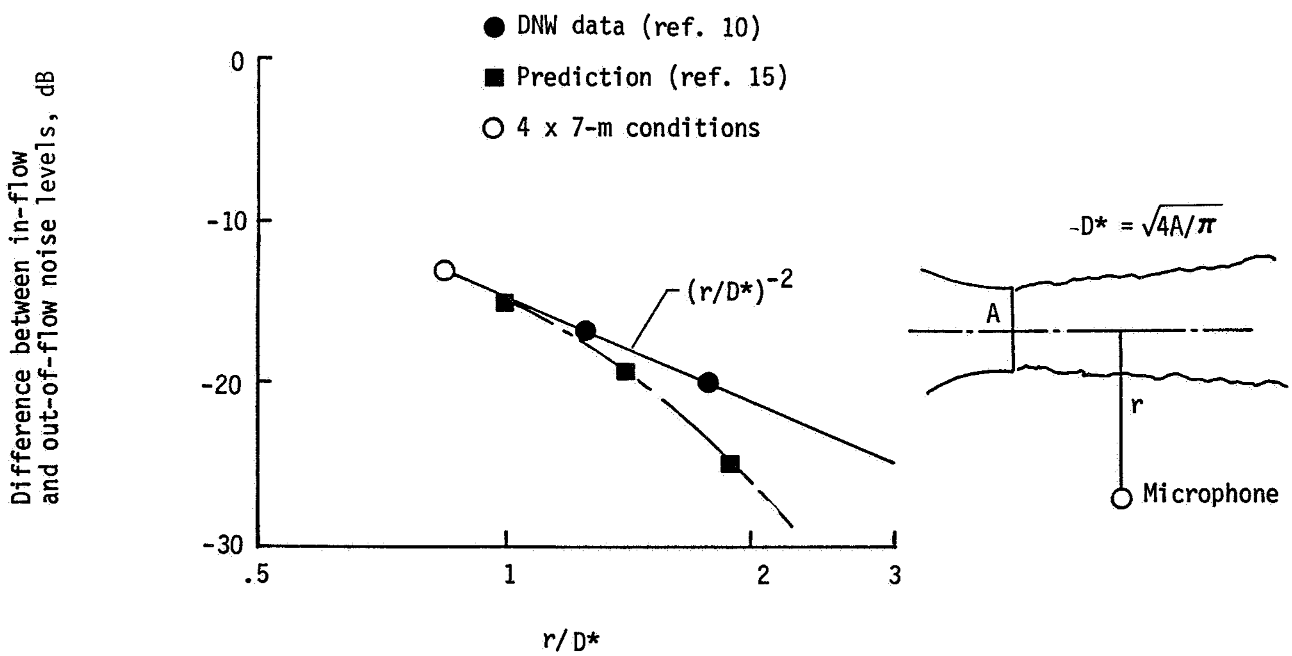


Figure 14.- Scaling of out-of-flow background noise reduction due to test chamber acoustic treatment. Tunnel speed, 120 knots; A denotes nozzle exit area.

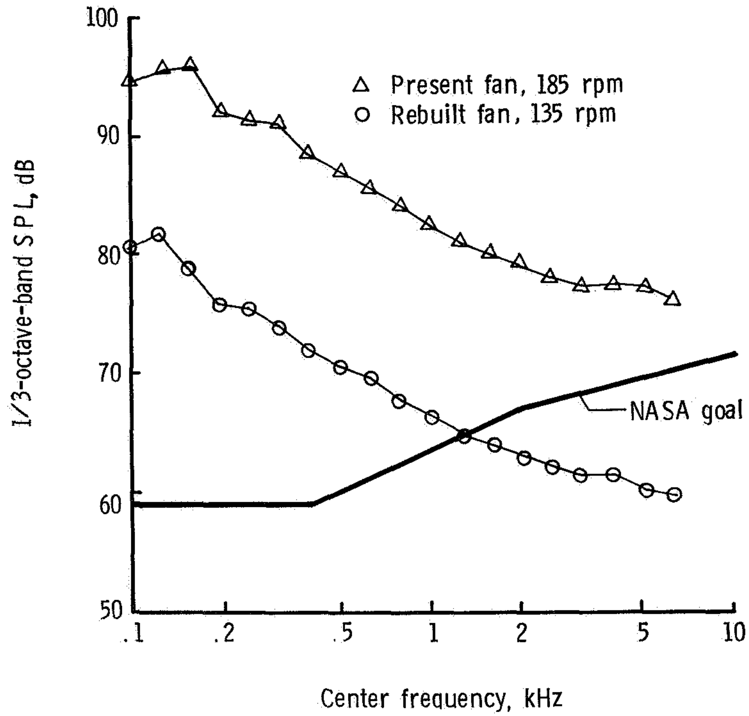


Figure 15.- Effect of rebuilt fan operating with a 27-percent speed reduction on out-of-flow background noise of 4 × 7-m Tunnel. Tunnel speed, 120 knots.

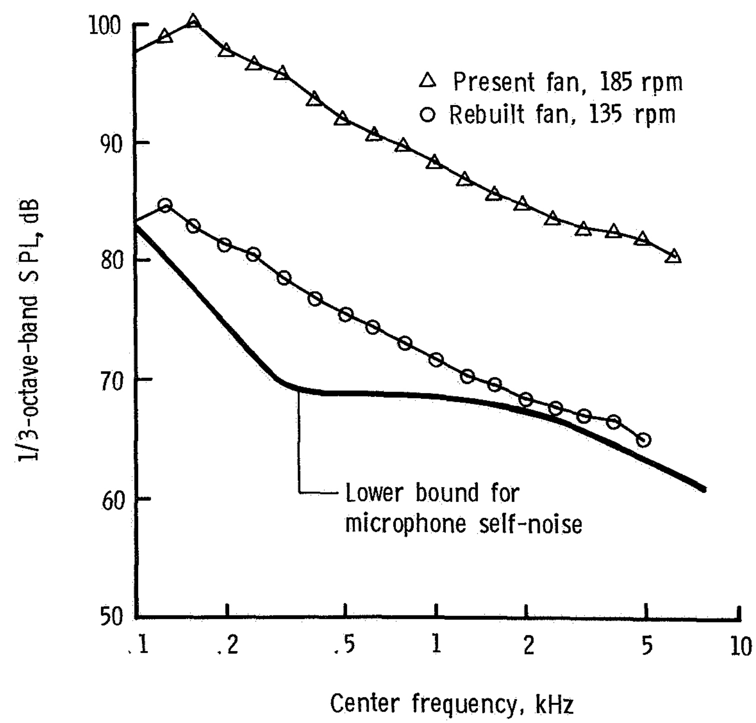


Figure 16.- Effect of rebuilt fan on in-flow background noise of 4 × 7-m Tunnel. Tunnel speed, 120 knots.

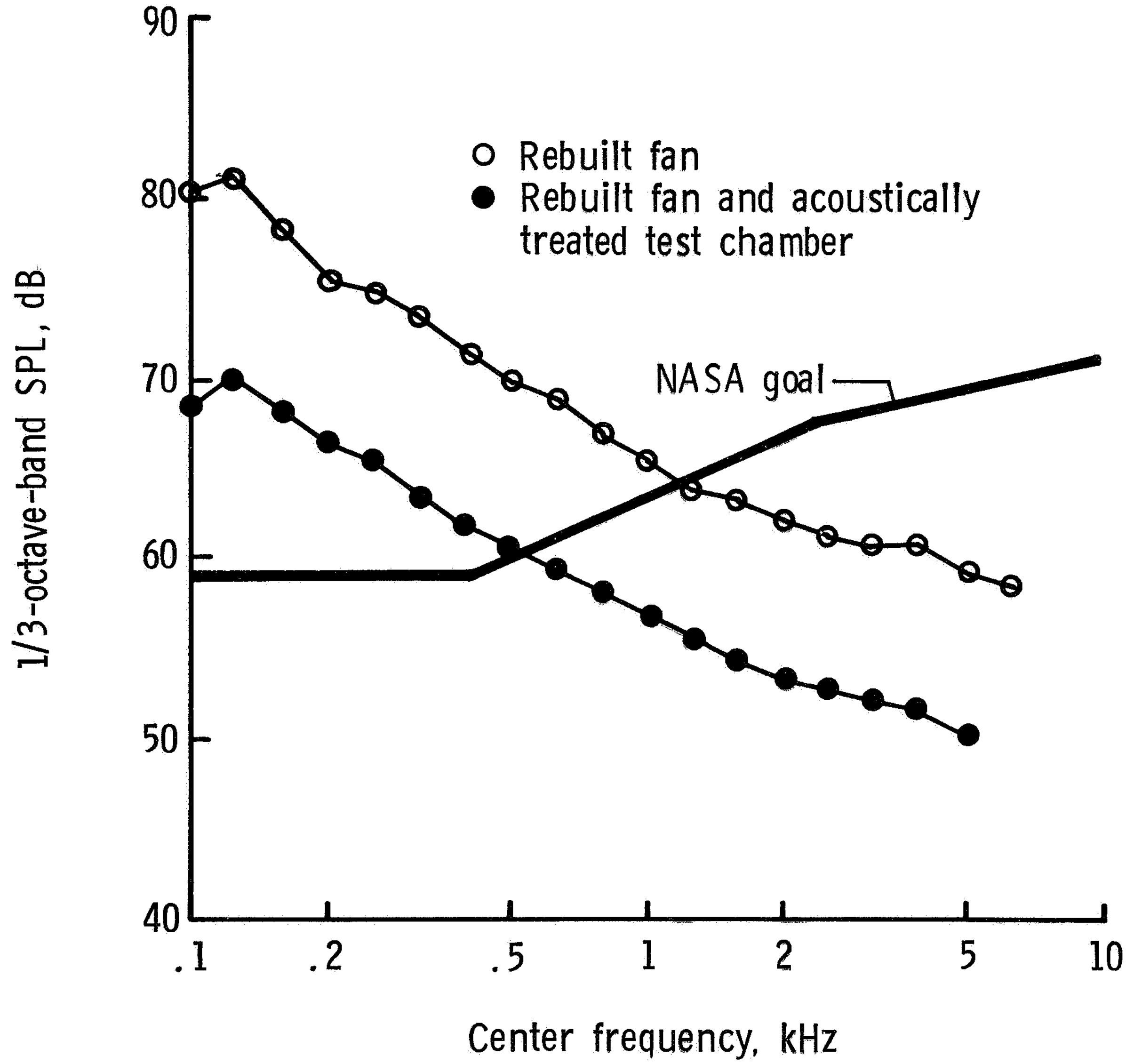


Figure 17.- Effect of rebuilt fan and test chamber acoustic treatment on out-of-flow background noise of 4 × 7-m Tunnel. Tunnel speed, 120 knots; out-of-flow microphone 5 m from tunnel centerline.

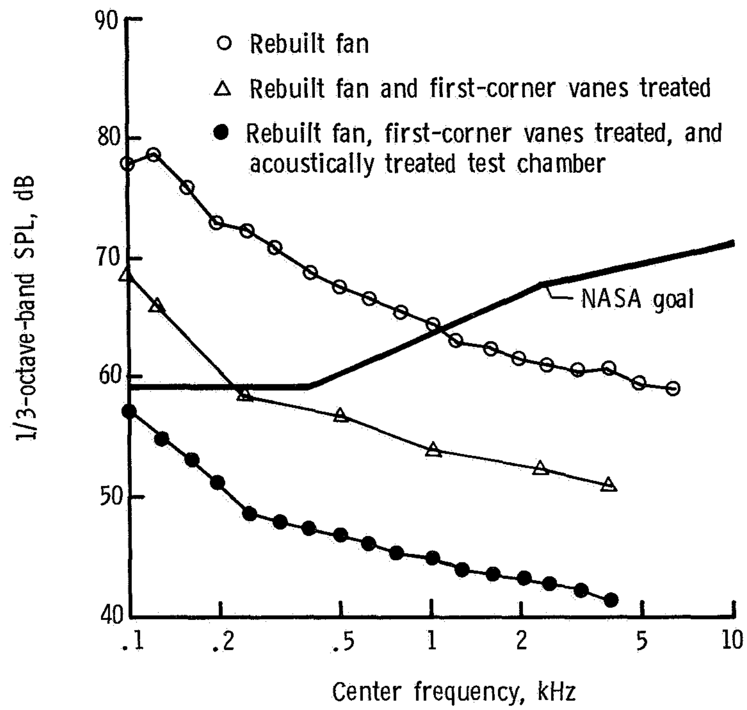


Figure 18.- Effect of rebuilt fan and acoustic treatment on out-of-flow background noise of 4 × 7-m Tunnel in upstream path. Tunnel speed, 120 knots; out-of-flow microphone 5 m from tunnel centerline.

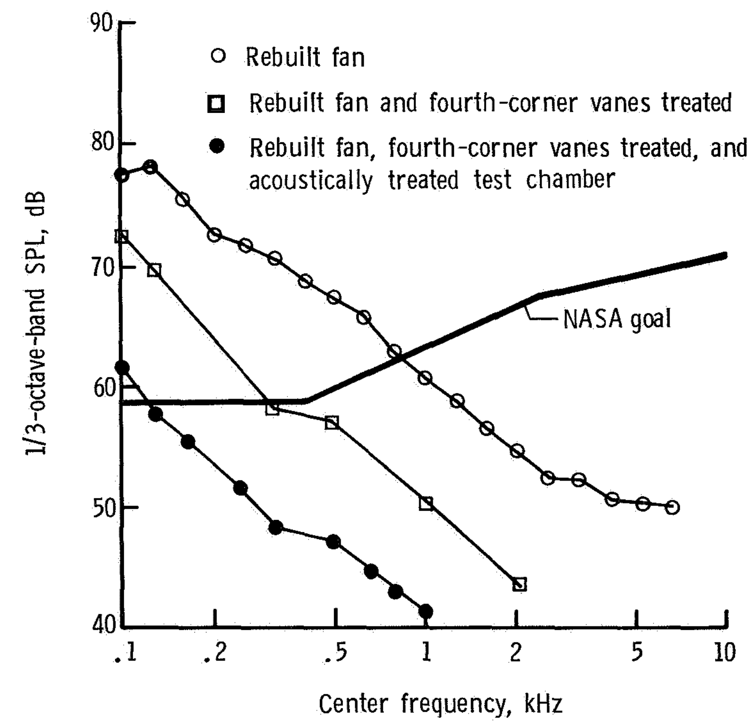


Figure 19.- Effect of rebuilt fan and acoustic treatment on out-of-flow background noise of 4 × 7-m Tunnel in downstream path. Tunnel speed, 120 knots; out-of-flow microphone 5 m from tunnel centerline.

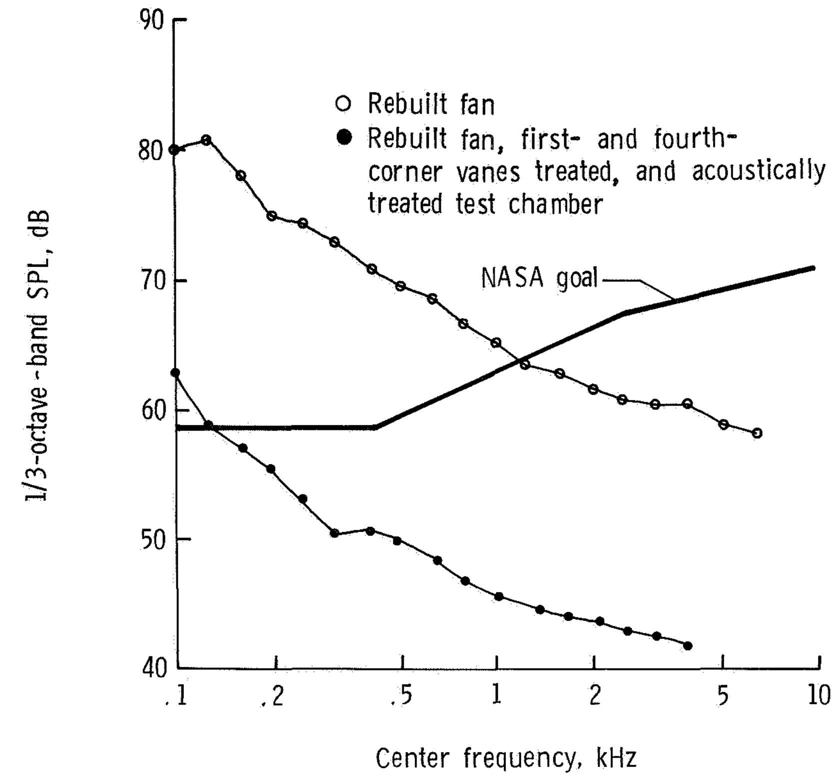


Figure 20.- Effect of rebuilt fan and acoustic treatment on out-of-flow background noise of 4 × 7-m Tunnel. Tunnel speed, 120 knots; out-of-flow microphone 5 m from tunnel centerline.

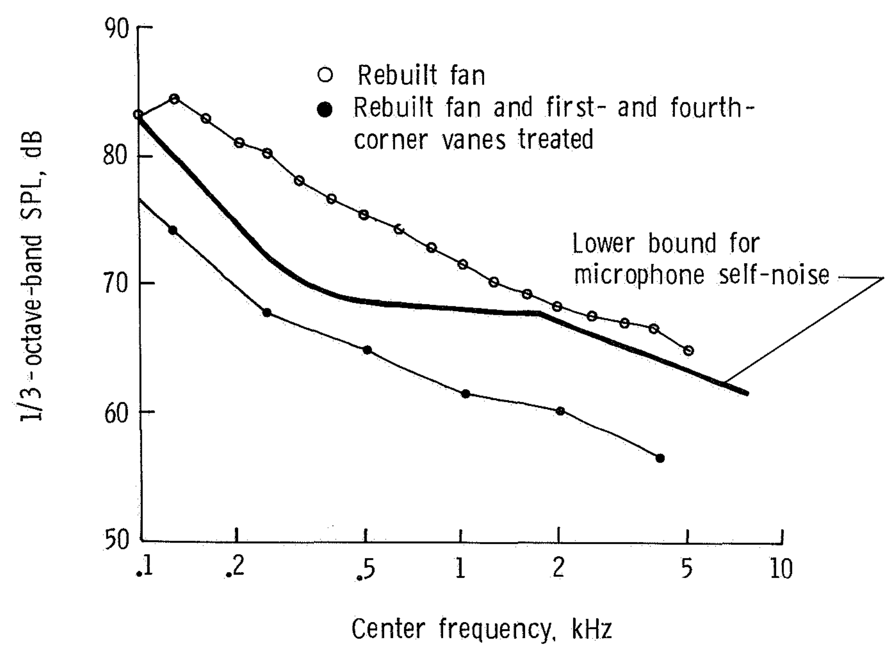


Figure 21.- Effect of rebuilt fan and acoustic treatment on in-flow background noise of 4 × 7-m Tunnel. Tunnel speed, 120 knots.

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A. Louis Abrahamson: COMTEK, Grafton, Virginia.

16. Abstract

This report describes a feasibility study for upgrading the NASA Langley 4- by 7-Meter Tunnel so that it may be used for aeroacoustic research related to helicopters. The requirements for noise research leading to the design of the next generation of helicopters impose a set of acoustic test criteria that no existing wind tunnel in the United States can presently meet. Included in this feasibility study are the following considerations: (1) an evaluation of general wind-tunnel requirements and desired tunnel background noise levels for helicopter aeroacoustic research, (2) an assessment of the present acoustic environment for testing model rotors, (3) a diagnostic investigation of tunnel background noise sources and paths, (4) acoustic treatment options for tunnel background noise reduction and a trade-off study between these options, (5) an engineering feasibility assessment of the selected option, and (6) an integrated analysis of study components and recommendations of treatment for an approach to meet the tunnel background noise reduction goal. It is concluded that the Langley 4- by 7-Meter Tunnel is a fundamentally suitable facility for helicopter aeroacoustic research. It is also concluded that acoustic treatment of this facility for meeting the required tunnel background noise goal can be accomplished technically at reasonable risk and cost.

17. Key Words (Suggested by Authors(s))
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